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Article

DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia

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Abstract: Design for manufacture and assembly (DfMA) is an important part of the future of the construction industry due to the promise of speed of project delivery, quality control, worker safety, and waste minimization onsite via the purposeful design for manufacture and assembly offsite. However, the adoption of DfMA in Australia has been slow. This paper investigates the barriers prohibiting widespread uptake and how digital construction will be a catalyst for improving use on commercial-scale projects. A total of six leading experts were interviewed to elicit their opinions, and seven recent case studies of high-rise modular apartment and hotel buildings constructed by Hickory were cross-referenced as evidence of DfMA capability. The experts suggested that the reasons for slow adoption in Australia were community mindset, government regulations and incentives, planning and building codes, unionization and business politics, finance, and supply chain management. The case studies suggest that compatible building type and transportation distance are also factors. These barriers can be addressed by the clever integration of building information modelling tools with lean construction processes as part of a proposed strategy leading to smarter (more productive) and better (more sustainable) outcomes predicated on growth in digital construction practices. The paper concludes with a proposed framework for change that conceptualizes the ‘ecosystem’ needed to support widespread DfMA in the Australian context, including the paradigm shift from building to manufacturing/assembly, the displacement of workers from onsite to offsite activity, and the expansion of interdisciplinary design and construct collaboration.

Keywords: design; manufacture; assembly; lean construction; waste minimization; Australia



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1. Introduction

Construction is one of the largest sectors in the world economy and is a crucial industry in many countries. According to McKinsey & Company [1], about 13% of global GDP is spent on related goods and services every year. Demand is still proliferating. Design for manufacture and assembly (DfMA), which was developed over 50 years ago and has been widely used since the 1980s to simplify designs for products and increase time and cost efficiency in manufacturing [2], offers promise for achieving a more productive and sustainable construction industry.

A Plan of Work for DfMA, published by the Royal Institute of British Architects (RIBA) in 2013, defined DfMA in the construction industry as an approach that dramatically facilitates offsite construction and minimizes onsite construction [3]. RIBA also categorized DfMA into five levels—component manufacture, sub-assembly, non-volumetric preassembly, volumetric preassembly, and modular building. In the same year, industry giant Laing O’Rourke released a paper advocating that, in their opinion, DfMA was the future of construction [4].

In the United Kingdom (UK), Modern Methods of Construction (MMC) is an umbrella term that is generally used to reflect a series of technical improvements in prefabrication, including a number of onsite and offsite construction methods [5]. DfMA incorporating Building Information Modelling (BIM) is considered as an advanced approach to MMC [6].

The UK government advocated it as a major strategy to achieve the ambitious targets planned in Construction 2025 [7]. An industry-leading company, Balfour Beatty, committed to reducing onsite activity by 25% by 2025 through employing DfMA techniques to align with the UK government's blueprint [8]. The RICS (Royal Institution of Chartered Surveyors (<https://www.rics.org/uk>, accessed on 26 June 2021)) was also quickly onboard [9].

In Hong Kong, the publication Construction 2.0 identified three strategic thrusts, including DfMA, BIM, and design for buildability to transform the Hong Kong construction industry into an advanced future with innovation, professionalization, and revitalization [10]. The term Modular Integrated Construction (MiC), which is one example of DfMA, has been widely used in Hong Kong. By using MiC, free-standing integrated modules, usually complete with finishes, fixtures, and fittings, are manufactured via factory assembly lines and are then transported in modules to construction sites for installation [11]. To facilitate broader adoption for private building developments, the Hong Kong Building Department [12] established a pre-acceptance system for granting in-principle acceptance to MiC systems and components.

In Singapore, DfMA has been identified as a critical strategy to improve productivity in the construction industry and is greatly encouraged by the government. In 2011, the first Construction Productivity Roadmap was launched by Singapore's Building and Construction Authority (BCA) to achieve Singapore's national economic target after the global financial crisis [13]. In 2014, the adoption of DfMA was mandated as one of the conditions for Government Land Sales sites [14]. BCA also launched the second Construction Productivity Roadmap [15] to underpin the necessity of extensive adoption of DfMA to spur industry productivity. Prefabricated Prefinished Volumetric Construction (PPVC) is another vivid example of DfMA that is typically used in Singapore. This concept is similar to MiC, where building modules complete with internal finishes and fittings are manufactured in a factory environment before they are transported to a construction site for assembly [16].

In Australia, the construction sector contributes over AUD 360 billion in revenue, equating to about 9% of the national Gross Domestic Product. The Australia Industry and Skills Committee estimated that that will become an annual increase of 2.4% to the national economy over the next five years [17]. On the other hand, problems such as low productivity, intensive labour, high cost, and delays have not been addressed [17,18]. Despite calls for DfMA, it seems that its adoption in the Australian construction industry is still embryonic. Offsite manufacture (OSM) in construction and the influence that this would have on Australian productivity and sustainability is an under-researched topic [18].

DfMA is a methodology and design philosophy that originated from the manufacturing industry [19]. There were two stages in the development of DfMA—design for manufacture (DfM) and design for assembly (DfA)—which emerged in the late 1960s to early 1970s [2,20]. However, it took many decades before successful DfMA innovation was applied to construction. For example, Crowther [21] introduced the insights of design for disassembly to the area of reusing building materials to increase life cycle 'assemblability' based on DfA. Fox et al. [22] provided a strategy for successful application to buildings using DfM. Kim et al. [23] presented the suitability of precast components for standardized bridge construction in the UK by employing DfMA. Gao et al. [24] conducted a preliminary study of factors influencing DfMA adoption in Singapore. Yuan et al. [25] introduced a DfMA-oriented parametric design in prefabricated buildings. Wasim et al. [25] proposed an approach for sustainable, cost-effective, and optimized material design for the prefabricated non-structural components of residential buildings. Lu et al. [26] also reviewed the development of DfMA in commercial construction.

For the construction industry in particular, three DfMA perspectives are made apparent [13]:

- DfMA is a systematic process that incorporates design, manufacture, and assembly using DfMA principles and adds value to the overall process.

- DfMA is an evaluation system that can assess the efficiency and productivity of manufacturing and assembly combined with the use of virtual design and construction.
- DfMA is a game-changing methodology that is closely associated with ever-changing prefabrication and modular construction methods.

However, DfMA is unlikely to work in isolation. Apart from BIM, three important contexts are listed below.

1.1. DfMA and Lean Construction

Lean construction is defined as a way ‘to design production systems to minimize the waste of materials, time and efforts to generate the maximum possible amount of value’ [27]. DfMA and lean construction have been discussed as sharing a common philosophy [24,28]. Koskela [29] noted that DfMA could help to reduce non-value adding activities in construction. Gerth et al. [30] pointed out that DfMA and lean construction contribute to sustainability ideals by minimizing waste and the cost of rework during onsite construction. Similarly, Gbadamosi et al. [28] presented empirical evidence to show how DfMA can facilitate lean construction. The potential benefits of DfMA as part of a lean construction mindset have been recognized [26,31]. The practices of lean thinking, including pull-planning, design-to-cost, and standardization, are shared with DfMA [32].

The successful adoption of DfMA and lean construction practices can increase industry efficiency [28]. However, there are still some conceptual differences in scope. Lean construction aims to minimize construction waste, to reduce effort and time through proper production design, and to deliver over a supply chain system. In contrast, DfMA focuses on improving the efficiency and productivity of manufacturing and assembly from the early design stage [24]. Therefore, DfMA demands more measures for optimizing design, while workforce flexibility and delivery systems are not as significant as in lean construction [13,24]. Cerm-ex Technology claimed [33]:

“Using automated processes to manufacture construction components in a controlled offsite environment, DfMA allows us to calculate materials requirements with absolute precision. This way, the industry’s most sustainable construction solution allows us to eliminate waste from the outset and return would-be waste back into the production process. By taking work off site reducing onsite activities the construction process becomes inherently safer”.

1.2. DfMA and Prefabrication

Prefabrication is defined as a manufacturing process, generally undertaken in a factory setting, in which various materials are combined as products and systems ready for final installation [34]. According to the close evaluation of a contemporary application, Wasim et al. [35] presented DfMA as an approach to further enhance the benefits for the prefabricated non-structural components of residential buildings. In 2014, DfMA was identified as an important recommendation during the International Panel of Experts for construction Productivity and Prefabrication Technology in Singapore [13].

DfMA is a game-changing methodology [14] that is closely associated with ever-changing prefabrication [4]. DfMA solves problems by involving manufacturers and technicians upfront at the design stage and considering issues in manufacture and assembly. It is considered one of the most significant steps in prefabrication [26,36].

1.3. DfMA and DfX

Design for excellence (DfX) is a methodology developed to put the environment, recycling, disassembly, and life cycle assessment more prominently into the design of buildings to increase sustainability. ‘X’ refers to several aspects including testability, compliance, recyclability, manufacturability, reliability, maintainability, and variability. By using ‘X’, design flexibility, efficiency, productivity, and quality can be increased, and cost, waste, and time can be decreased [26,37]. DfX emphasizes the consideration of all design purposes and their related challenges in the early design stages. Though more additional effort might be

required to implement DfX, efficient transition to manufacturing and reduced life cycle cost can be achieved by combining business and management practices with technology instruments. More predictable products can be produced to meet consumer demands [37]. The phenomenon of embracing DfX in construction has yet to be seen [26].

1.4. Benefits and Challenges of Adopting DfMA

The connection between DfMA, BIM, and lean production has been identified as an important step in their adoption by the construction industry in the UK [38].

The advantages of DfMA are multifaceted. Reported DfMA case studies for commercial construction are listed in Table 1. The largest benefit reported by Laing O'Rourke [4] was program time reduction, which was also followed by better quality and safety. In the RIBA Plan of Work [3], it was reported that 20–60% of program time is reduced, 20–40% of onsite construction costs are lowered, and that there is 70% less onsite labour, with subsequent improvements in health and safety. Other benefits, included greater program certainty, better environmental outcomes, and fewer problems onsite, leading to less re-work and waste. Onsite cost savings must be considered in the context of higher offsite costs, and it is likely that overall savings will be predicated on industry transformation and widespread DfMA adoption in practice.

Table 1. Examples of DfMA applications in commercial construction.

Project Name	Contractor/Location	Offsite Content	Key Features of DfMA	Benefits of DfMA
Salford and Wigan Building Schools	Laing O'Rourke (UK)	70%	<ul style="list-style-type: none"> • Development of a library of standard structural components • DfMA development including prefabricated service risers, prefabricated services, horizontal distribution units, and packaged plant rooms • Application of digital technology 	Considerable reduction of time in the production of component drawings
Water Treatment Plant	Laing O'Rourke (Australia)	300 'module transportable packages'	<ul style="list-style-type: none"> • Offsite pre-assembled piping and electrical distribution 'modules' • 5 plant locations, 32 module groups, 262 modules in total including kits-of-parts • Application of digital technology 	<ul style="list-style-type: none"> • 70% reduction in site labour • 60% in project delivery time for DfMA components
Davyhulme Wastewater Treatment Plant	Mott Macdonald (UK)	5000 precast elements	<ul style="list-style-type: none"> • Development of a catalogue of 80+ DfMA products, predominantly for the water sector, including all the elements to create a sewage pumping station as well as more general components • Close liaison between the design disciplines to ensure each component provides the necessary structural and functional requirements • Application of digital technology 	<ul style="list-style-type: none"> • Material waste reduction • 3 months shorter in project delivery • Time savings of 50–90%

Table 1. Cont.

Project Name	Contractor/Location	Offsite Content	Key Features of DfMA	Benefits of DfMA
Leadenhall Building	Laing O'Rourke (UK)	85%	<ul style="list-style-type: none"> • First time DfMA used in earnest • 20 revisions before a final version was agreed upon in terms of floor systems • Application of digital technology 	<ul style="list-style-type: none"> • Increased the quality of materials and installation • Reduced site waste • Reduced overall site deliveries by 50%
Battersea Power Station Site Redevelopment Phase 1	Carillion and Skanska (UK)	Manufactured 540 utility cupboards	<ul style="list-style-type: none"> • The kit-of-parts construction system • Manufacturing takes place in a temporary facility rented for the duration of the offsite program • Virtual reality 	<ul style="list-style-type: none"> • 60% reduction in time • 4% cost saving • 73% fewer defects

Adapted from Gao et al. [24].

1.5. Knowledge Gap

Although DfMA has been considered to play a critical future role in the construction industry, researchers have indicated various challenges based on their investigations to date. First, the global industry lacks a suitable ecosystem, which includes relevant guidelines, standards, and affordable technologies for better adopting DfMA. Adequate experience, guidelines, and standards are essential for stakeholders to employ DfMA [26]. Architects and engineers may not have sufficient understanding of the process, manufacturing order, how parts should be assembled, and the leading time of onsite operation at the design stage [24,39]. Furthermore, social attitudes and user acceptance were pointed out as potential barriers by Lu et al. [40] and Pan et al. [41]. The gross capital cost of adopting DfMA may be considerable at an early stage, as new technologies and a suitable ecosystem require extra investment to support DfMA adoption [4,26]. None of the above research related specifically to Australia, and therefore, a knowledge gap has been identified in relation to institutional barriers that might be affecting the adoption of DfMA in the Australian context as well as unique strategies for dealing with them. The remainder of the paper addresses this knowledge gap through triangulated qualitative enquiry.

2. Materials and Methods

It is clear from the literature that the UK, Hong Kong, and Singapore are leaders in DfMA for commercial construction. Australia, by contrast, appears to be lagging. Therefore, the aim of this paper is to further examine DfMA adoption to identify barriers preventing its implementation in Australia. To achieve this, three objectives are suggested. First, a qualitative semi-structured interview method is employed to collect primary data [42]. Second, a total of seven Australian case studies are explored to demonstrate recent implementation capability. Third, a roadmap for digital construction integration to support further DfMA adoption in commercial construction projects is proposed.

The rationale for choosing interview as the primary research method is because it assists in obtaining facts, insights, or understanding interviewees' attitudes, opinions, processes, experiences, or predictions [43] that are not available in the literature. Moreover, semi-structured interviews not only cover specific questions, but also allow interviewees to have a great deal of leeway in how they reply [44]. Additionally, due to a mutual background or relevance system between interviewers and interviewees, the motivation level to attend an interview can be increased. Future justification can be greatly eliminated due to a shared understanding of the social relevance of research, which can be assumed [45].

A total of six experts holding substantial experience in the construction industry, the visibility of DfMA projects, and who are familiar with its relevant concepts were purposively selected for interview. Within the qualitative literature (and community of practice), the concept of ‘saturation’ is important. This is defined as the point when new data only create new managerial insight into the problem at hand [46]. Morgan et al. [47] demonstrated that 5–6 expert interviews were satisfactory for most concepts. Guest et al. [48], in a systematic inductive thematic analysis of 60 in-depth interviews among female sex workers in West Africa, found that of the 114 themes identified in the entire dataset, 80 (70%) turned up in the first six interviews. Other researchers have confirmed that 6–12 interviews seem to be a sweet spot for the number of qualitative interviews needed to reach saturation, and it is likely that the level of expertise of those being interviewed suggests the lower end of that scale as more appropriate, especially if more fine-grained themes are sought. [49–52]. The best answer to ‘how many is enough?’ is ‘it depends’. Part of the consideration includes epistemological and methodological questions about the nature and purpose of the research: whether the focus of the objectives and of analysis is on commonality or difference or uniqueness or complexity or comparison or instances [53–55].

Expert A has worked in Singapore and is now based in Melbourne. He is an international expert and has extensive knowledge in construction-based DfMA from Singapore, Hong Kong, and the UK. Expert B is a DfMA specialist in Sydney having worked in the construction industry for over 20 years, including on modular school construction projects in New South Wales. Expert C undertakes research into OSM and has construction experience in Africa, New Zealand, and Australia. Expert D is based in Hong Kong, has published widely on DfMA, and has strong connections in Australia. Expert E operates his own modular building company on the Gold Coast and has a primarily business/entrepreneurial background. Expert F works in Brisbane, has over 40 years of construction and property development experience, and has a keen interest in affordable housing.

Invitations and an outline of basic questions (as shown in Figure 1) were sent out prior to the interviews, providing the experts with a clearer idea of the study theme and assisting with the flow of the interview process. Supplementary questions were also prepared according to the background and interests of the experts. Other questions arose during conversations.

Research ethics for this study were governed by the Bond University Human Research Ethics Committee (BUHREC). Relevant information to assist with the interviews included an Explanatory Statement and Participant Consent Form, which were sent prior, and interview transcripts using Otter recording software and copious notetaking during the interviews. The approved BUHREC Protocol Number for this study was 15170. Interviews were conducted between February and March 2021.

Due to the impact of the COVID-19 pandemic and the associated constraints placed on traveling, online meetings were the only feasible option. A large amount of traveling time was saved. It was recognized that the convenience of online meetings also makes potential interviewees more willing to participate in the study. The online forum removed some potential bias from the interviewers [56,57] and enabled the procedure to be more transparent and efficient. On the other hand, however, mutual linking and richness of communication might be reduced. The problem of maintaining internet connection stability was a risk factor.

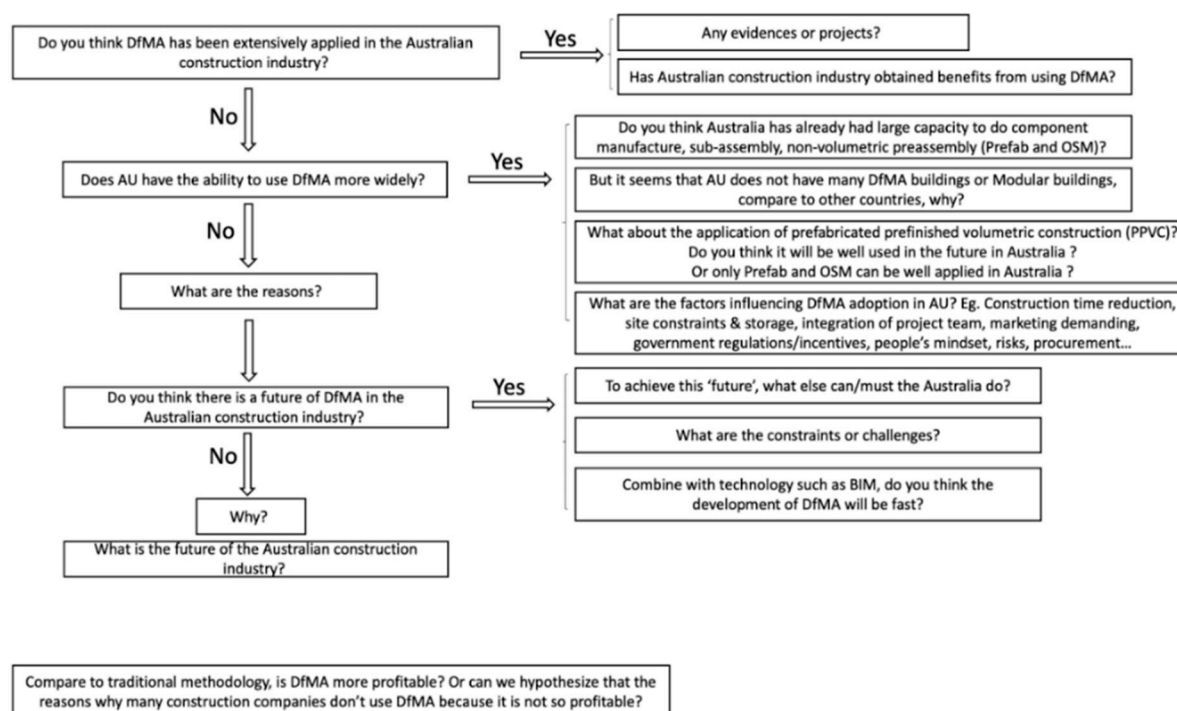


Figure 1. Outline of core interview questions.

3. Results

3.1. Adopting DfMA in the Australian Construction Industry

Experts expressed their opinions on whether DfMA has been extensively applied in the Australian construction industry. There was a mixed response. Expert F answered in the negative and commented that the industry uses prefabrication rather than DfMA. There were four experts, however, who answered in the affirmative. They believed that Australia has implemented DfMA in non-residential construction projects. There was one interviewee who responded both 'yes' and 'no'. Expert C explained:

"We should look at a material perspective. Among three major construction materials, steel, concrete, particularly precast concrete, and timber, not all of them have been combined with DfMA, but engineered timber, such as cross-laminated timber, is being applied extensively. Australia has the capacity to make DfMA-based high-rise modular buildings using timber but not precast concrete".

None of interviewees doubted Australia's capability or capacity to employ DfMA in construction. Expert E pointed out that the modular housing market used to be considered as a secondary market, but nevertheless had a positive perception that modular housing was experiencing growing demand.

Some experts mentioned that Australia must adopt DfMA. Expert A stated that: "Australia has good performance in using timber, and timber as a more environmental and light material, can be easily manufactured offsite then transported to site, then stacked together like Lego". Expert A identified recent case studies of high-rise commercial buildings using stackable structural modules in Melbourne that should be explored as part of this research.

Expert D made similar comments about the advantages that Australia has for further employing DfMA. He expressed that: 'compared with Singapore or Hong Kong, Australia produces raw materials, very good steel, iron ore and concrete', and believed that Australia has the ability and capacity to build an industrial supply chain for prefabricated components and systems and the flexibility to choose either domestic construction resources and/or import materials from overseas.

3.2. Barriers

Although Expert A gave a clear view that the Australian construction industry has the capability to adopt DfMA, it is not common to apply DfMA on whole buildings. Expert A provided several reasons that constrain the development of DfMA in Australia. The first reason is the limitation of market scale. The second is related to higher costs compared to traditional construction. Developers who are profit-driven are reluctant to adopt DfMA. Third, government support and incentives are inadequate. In addition, unionization is another barrier to further adopt DfMA. Expert A mentioned that:

“to employ DfMA, two types of workers are required, one is labour, and the other type are workers with design ability. The core workers in Australia are the former who are onsite. They are protected by unions that will not allow workers to be unemployed. The union is very large, so it is difficult to change for a while”.

Expert B stated three major reasons that challenge DfMA adoption in Australia. The first is mindset. Expert B explained three aspects related to this:

“People commonly think modular buildings mean square boxes, death of good architecture, or temporary places to stay. In addition, people are conservative and oppose to new things. Then, people think that they don’t need to change on site to offsite because they still make loads of money onsite”.

The second reason mentioned was risk:

“A whole new realm of risk is opened up when the new methodology is adopted. Risks are rolled downhill from clients to contractors then to subcontractors in a traditional procurement process when contractors don’t know how to price projects when they do these new things”.

Government was the third reason. Expert B believed that government drivers and commitments are essential to transition to offsite construction. A committed pipeline needs to be created by state governments for the industry before it rolls into procurement.

Expert C added that: ‘it is not just one person or one source’. The first problem was that the contractors who stick to traditional roles do not like change. The second was the slow response of designers for design solutions for customers who demand quick feedback in a few days. Council authorities treating innovation as a risk was the third challenge, and hence, there are problems having projects approved by them. The fourth challenge was that banks do not provide funding if something has not been tested or if it is not popular. Expert C also alluded to the influence of digital engineering on the future of the local industry.

Expert D was concerned that flexibility is a limitation for DfMA adoption. Taking Hong Kong as an example, developers in the private sector are not willing to use it because its flexibility does not meet their requirements. For those private sector developers, it is common for them to change the design at any stage for marketing purposes. Modules based on DfMA concepts cannot be changed onsite, while they can when cast in situ. For this reason, cast in-site is preferred, and DfMA/prefabrication has not been as popular.

There were two constraints that were mentioned by Expert E. The first reason was that the government has too many regulations while offering inadequate incentives or leadership. The other constraint was logistics. Transportation problems have happened when Expert E’s company started to ship housing pods.

Expert F stated four reasons that constrain the adoption of DfMA in Australia. The first reason was the unions, who are against DfMA adoption because it would cost them jobs on the construction site. The second was planning constraints. The Australian planning codes consider modularized type construction as second class, the building codes are geared more towards bespoke construction rather than modular construction. The third was people’s thinking. The final one was finance. Expert F said that the banks, particularly in the housing sector, would not provide a traditional mortgage on modular construction; hence, customers would have to have a very short-term and expensive loan compared

to normal housing mortgages, and the valuation profession also tends to downgrade the value of modularized construction.

Expert F also commented that the mixture of power between various levels of government (federal, state, and local) and the persuasions of the governing Labor or Liberal coalitions introduces the issue of politics. DfMA adoption could sacrifice some current vested interests as well as create future opportunities for greater national industrialization.

3.3. The Future of DfMA

Experts showed both positive and conditional perspectives concerning the future of the Australian construction industry. One comment made:

“It takes quite a long time for the construction industry to adopt that way to combine high technology in this industry. It’s like a bright future but still takes time and costs a lot to get that point”. (Expert B)

Higher levels of digital construction and engineering need to be achieved to support DfMA:

“In order to harness the power of DfMA, a lot of upfront work should be considered and done at the design stage. Digital technology facilitates this stage. At manufacturing and assembly, digital technology provides transformation. And future construction is a digital transformation, it doesn’t just only transform some current technology, but also transforms the traditional construction mode to more on DfMA, more modular”. (Expert D)

Expert D also mentioned the application of BIM, RFID, Auto-ID, laser scanning, QR codes, and blockchain regarding future construction and gave a brief example of employing BIM, which connects a cyber system and a physical system, combining RFID and echo technology, to create modules used for DfMA. Expert D suggested that Australia needs a roadmap to guide its future development in this area.

There was a consensus on the capability of adopting DfMA in the Australian construction industry among all of the experts in this study. Recent commercial cases in Australia show the capacity of the local industry to employ DfMA. La Trobe Tower, La Trobe Street Student Accommodation, Peppers King Square, Collins House, Holiday Inn Express, Ovolo Hotel, and Holiday Inn Express Little Collins were seven high rise modular buildings (RIBA Level 5) completed in the last five years [58]. All but one of these buildings are in Melbourne, Victoria. The developer, Hickory, is considered a pioneer of innovative modular buildings in Australia. A unique volumetric structural system named Hickory Building System (HBS), which is a state-of-the-art concept that integrates the core, facades, shear walls, and bathrooms into the building structure, was used on the tower component of all seven case studies. This system is a great example of DfMA benefits. Evidence shows 30–50% of construction time can be reduced by using HBS; at the same time, materials and energy waste are minimized, and safety and quality are increased [18].

La Trobe Tower is a 44-storey residential building comprising 206 apartments. It had a 19-month construction period and was completed in November 2016. It was Hickory’s first use of HBS at scale. A 30% time reduction over traditional construction methods was achieved. Modules were transported to the site and were lifted to the designated level overnight. 3D modelling and design validation was combined with the employment of BIM to assist the structure mapping and three-dimensional consolidating.

La Trobe Street Student Accommodation, which comprises two buildings of 44 storeys and 7 storeys, was completed in November 2018 after 22 months onsite. A total of 619-bathroom pods were prefabricated offsite and were finished with plumbing, lighting, joinery, walls, and floor coverings and were then transported to the site from Hickory’s own factory in Melbourne. The construction program saved time by 30%, owing to use of the HBS method. The project won one of the Council on Tall Buildings and Urban Habitat (CTBUH) Awards for Excellence in 2019.

Peppers King Square, constructed over 19 months in Perth, Western Australia, is a 17-storey hotel with 120 studio apartments. It was completed in November 2018. The

installation of the prefabricated units was undertaken in just 11 weeks. It represented Australia's tallest prefabricated hotel at the time but required the development of local manufacturing capability nearby.

Collins House is a 60-storey 259-apartment residential building completed in September 2019. It is the slimmest high-rise building in Australia. The implementation of the HBS method allowed for the use of large building components prefabricated offsite, which were then transported and installed onsite. Only one crane and hoist were used, and assembly time was less than one hour per module, which significantly reduced the disruption to traffic and local surroundings. Floors were perfectly leveled through innovative upside-down prefabrication during manufacture, and the replacement of temporary props by pre-installed push-pull connections for the façade vastly increased the efficiency of installation onsite. Collins House won a CTBUH Construction Award for Excellence in 2021 [59].

Holiday Inn Express is 23 storeys and contains 345 hotel rooms. It took 18 months to build and was completed in November 2019. The bottom 8 floors were constructed using conventional techniques and the remaining 15 floors were built using HBS. It achieved a 5-star energy rating.

Ovolo Hotel, built in Melbourne's South Yarra, comprises 6 levels and 123 rooms. It took 12 months to build and was completed in December 2020. Its speed of construction should be viewed in light of COVID-19 restrictions, which included construction sites in Melbourne, requiring them to operate at 50% capacity.

The final case study is Holiday Inn Express Little Collins. It is a 33-storey mixed development including 24 floors of prefabricated hotel rooms. It is now the tallest prefabricated hotel in Australia. It took 30 months to complete despite a series of COVID-19 lockdowns and was finished in June 2021.

HBS is a prefabrication approach for high-rise buildings that have significant floor plan compartmentalization. It is not readily applicable to large span office space or building designs that have overhangs and/or setbacks in their external façade. Transportation and onsite assembly largely take place at night to avoid local traffic disruption.

Hickory claims to be Australia's leading apartment builder [18]. Meriton might disagree. Its system of high-rise prefabrication works well for this type of construction. Its features include:

- The lighter unified structure of HBS enables Hickory to build on sites that would not otherwise withstand the weight of a more conventional building approach.
- There is potential to add several levels to high-rise projects given their fixed height limits without compromising internal ceiling clearance due to HBS floor-to-floor height advantages.
- Bathroom pods are fully enclosed and installed complete with all services, fittings, lighting, and finished wall surfaces, thus limiting onsite trades and raising finished quality.
- The external integrated façade is pre-attached in the factory and aligns precisely with neighboring structural units when installed onsite.
- HBS allows considerable freedom in scale and does not pose significant restrictions on building layouts or apartment size and configuration.
- Post-tensioned beams can be integrated into the concrete floor of each prefabricated unit as 'wet joints' and connected to in situ post-tensioned beams onsite.
- Recesses for prefinished bathroom pods are incorporated into the lightweight precast floor slabs to ensure smooth transitions at the floor level.
- Flexible structural unit size is scalable from small to large aspect ratios within the parameters of road transportation.

Hickory [18] state that HBS can also be applied to hospitals and health care centers, but no evidence was found to support that. HBS can be specified for projects up to 70 storeys high. Hickory's manufacturing and construction divisions work together to coordinate the supply chain logistics and ensure that assembly onsite is minimized

to provide time savings. There is no available evidence, however, of overall project cost savings.

Modules must be transported via road, and hence, the local conditions will dictate size constraints (width and length) as well as requiring delivery and installation at night when the streets are not as busy with traffic. This is part of the reason for delivery speed since construction sites are in operation after hours. Examples of prefabricated modules constructed under controlled conditions in a factory and transported to Melbourne CBD sites are 12 m × 3 m × 3 m (20 tonnes) and 17 m × 4.5 m × 3 m (26 tonnes) [60]. Hoisting times are fast but are still constrained by delivery capacity and onsite parking access while hoisting modules into place.

HBS reduces the risk of objects (tools, materials, etc.) falling from upper floors since the structure arrives with pre-installed façades and requires limited work at height on the building edge. Scaffolding is not required. The benefit of this integrated approach is evident, with HBS projects recording zero incidents of falling objects to date [18].

4. Discussion

From the previous case studies and the views of the six experts, it is evident that Australia can adopt DfMA well in construction programs including high-rise buildings that demand high standards and rigorous requirements. However, the application of DfMA is still low in Australia. Existing literature provided little information affecting DfMA adoption in the construction sector, especially in the context of Australia. There were six barriers that were identified in this study:

- Community mindset.
- Government regulations and incentives.
- Planning and building codes.
- Unionization and business politics.
- Finance.
- Supply chain management.

Each of these are discussed individually in the following sections.

4.1. Community Mindset

The common mindset of modular and prefabricated buildings typically means square boxes, the death of good architecture, or that they were only meant to be temporary low-quality buildings. With this fixed image of DfMA-based structures, it is difficult for consumers to overcome this barrier. Moreover, people are conservative and lack a mindset of accepting new products, technologies, and methodologies.

Furthermore, DfMA-based construction is not common in Australia. Most of them are in the CBD of major cities; therefore, it is more challenging to enable conservative customers to see the development or the prospects of DfMA adoption more widely.

4.2. Government Regulations and Incentives

In most countries, the government is the largest construction client. Government regulatory systems and support are needed to implement innovations, including DfMA methodology. Certain countries have been open to adopt DfMA and to set up long-term goals to develop it. As previously mentioned, the Singapore government has advocated DfMA adoption, especially PPVC, and provides detailed guidebooks and support for employing DfMA. In China, the government has a well-defined vision for the adoption of DfMA. The Hong Kong government has also set up incentives for the construction of public housing. Private developers can get gross floor area concessions when MiC is implemented in their projects [31]. In the UK, to meet the target of delivering 300,000 homes annually, the government has realized that a significant proportion of buildings must be built using MMC. A series of supports, including finance for homebuilders to implement the innovative method, are offered by the government [61].

The absence of government regulations and support were considered factors in the adoption of MiC [62]. This is aligned with expert opinions in the present study. It is identified that the influence of the government is critical to broaden the application of DfMA all over the world. The same applies to Australia. The Australian government has not provided adequate attention, incentives, or suitable regulations to support the adoption of DfMA. The relation between supply and demand is ruled by the market itself; therefore, when government support is inadequate, marketing cannot be expected to support new directions. In addition, some incongruities between the federal government and state governments make establishing new regulations and providing incentives more complicated.

4.3. Planning and Building Codes

Codes and standards are set up as frameworks to ensure that the design and construction fulfill requirements such as zoning regulations, structural adequacy, access and egress, fire resistance, services and equipment, energy efficiency, and sustainability. Due to the differences between conventional construction and DfMA-based construction, Australian codes and standards that are suitable for the former are often not applicable to the latter. The inflexibility of using current regulations significantly inhibits DfMA adoption.

In Australia, timber has provided many benefits. Not only are the design options, performance criteria, and sustainability credentials of timber extensively recognized, but its material attributes of renewable, reusable, clean, and low energy during manufacturing are also greatly appraised [63]. Timber construction can enhance cost efficiency due to the reduction of onsite labour costs, less environmental impact, and lower running costs for owners. Furthermore, the efficiency of offsite manufactured timber construction is considerably higher than that of onsite technology [64].

It would be ideal to use timber as one of the major construction materials followed by employing DfMA, designing and manufacturing offsite, and then transporting the integrated parts to the site and assembling them onsite. However, timber has not yet been used as a key material for DfMA in Australia, possibly due to current building codes and a lack of empirical testing outside of residential projects. Obviously, without clear or adequate building codes, risks could be raised when a new approach is applied, especially when significant capital funding may be required.

4.4. Unionization and Business Politics

Trade unions have played an important role in Australian history. They have had great influence for the monitoring and enforcement of minimum employment standards—an essential part of the regulatory function of unions under the conciliation and arbitration system [65]. Unlike some countries such as Singapore and Malaysia, where foreign workers are the primary labour source contributing to their construction industries, most construction workers are typically permanent residents in Australia. They are part of important support for local economies. However, a lot of construction workers, especially those who provide onsite labour, would easily lose their jobs due to the increased efficacy and productivity brought by the adoption of DfMA. The unions are reticent to allow jobs to be slashed. Therefore, they are against using DfMA. Resistance from the unions has become one of the major challenges in the adoption DfMA in Australia.

Beyond unionization, politics in the construction business is another subtle barrier that impacts the adoption of DfMA in Australia. For example, contractors and subcontractors usually have long-term agreements with large organizations who dominate the market share of traditional construction materials. In this case, contractors and subcontractors are not willing to break agreements to adopt DfMA.

The union and business politics cannot be changed in the short term because it is part of the country's industrial system. However, onsite labour could be retrained over time to take up new offsite jobs in manufacturing. This requires a major shift in the way the construction industry is presently structured, with significant government support.

4.5. Finance

It was reported that time savings of 30% could be achieved on average by employing DfMA in construction projects [66]. DfMA-based construction indeed can have an overall cost reduction compared to traditional construction mainly due to a shortened construction program time. However, higher quality manufacturing processes may offset this advantage where economies of scale do not exist [67,68]. This point of view is aligned with the previous literature review and was confirmed by the expert interviews. Traditional construction methodology remains a primary option since developers or contractors are resistant to DfMA adoption due to perceptions of higher initial cost.

Furthermore, equity and debt capital markets in Australia may not be aware of the wider benefits of adopting DfMA in construction, or perhaps they are not so comfortable loaning funding to support DfMA-based projects.

4.6. Supply Chain Management

A key reason for using DfMA is to reduce the parts assembled onsite and to integrate as many parts as possible offsite based on a proper design [1,13]. Those integrated parts are typically large and cumbersome. Therefore, transport to sites, larger vehicles, cranes, and/or hoists are necessitated, and extra caution is required [8,24].

Furthermore, Australia is a large, urbanized country, so the distance between major cities is great. If logistics are not efficient enough to deliver modules from manufacturers to construction sites, the opportunities to build DfMA projects are limited [19,34]. It is hard to send large modules from manufacturers that are usually located in major cities and their adjacent areas to remote locations.

4.7. Reflection

Apart from considering the major constraints challenging DfMA adoption, it is crucial to consider lean construction, value management, design for excellence, life cycle performance, and related value-adding concepts. In addition, the blueprint for a DfMA methodology requires skills, expertise, experience, and technology. Prototyping, testing, just-in-time delivery, and a greater use of Agile project management methods can also be activated as appropriate.

To adopt DfMA, a higher level of specialization is key to applying it successfully. DfMA requires integrating construction processes in the early design stage, indicating that cross-disciplinary training is essential for all stakeholders involved in the design stage. The differentiation between onsite and offsite is predominantly in higher level skills [38]. Therefore, critical roles such as planners, designers, architects, structural engineers, and project managers will be affected by the requirements of upgrading skills and knowledge.

Moreover, future construction will be a function of digital transformation, which primarily relies on tools and processes. It is necessary to embrace powerful technology to adopt DfMA. Examples are BIM and lean construction but associated with these are technologies such as laser scanners for working within existing structures, Auto ID and QR/bar codes for logistics and supply chain management, and data analytics for evaluating performance efficiencies. Innovation is an implied characteristic of DfMA. It is more likely that research and development will be undertaken by specialist manufacturers compared to onsite contractors.

BIM is an essential tool for DfMA. Interoperability is a critical interface to enable data between different project participants to be shared. Expert A emphasized that BIM is not substitutable when DfMA is applied but is a unifying platform for design and construction (whether offsite or onsite). By using this platform, the project's scope, coordination, material tolerances, and data sharing can be properly managed.

According to Laing O'Rourke, three critical components of DfMA envelopes are geometry, production, and metadata [4]. All practical DfMA projects should employ a comprehensive digital communication strategy at their core [69]. Digital engineering entails more than 3D spatial modelling; more importantly, information including time, logistics

programming, initial investment, energy modelling, parametric data, asset tracking, and life cycle performance modelling are all fundamental [4]. BIM greatly assists in collaboration and transparency in this integration. Additionally, the industry must be open to new technologies and software to harness value and achieve optimum outcomes [70,71].

The global leader in DfMA software is Boothroyd Dewhurst Inc. (Warwick, RI, USA) [72]. In 1977, Geoffrey Boothroyd developed a DfA method that enabled manufacturing to the time required to assemble a product manually and the cost of assembling it automatically using a machine. He partnered with Peter Dewhurst to develop a computerized package of the DfA method in 1981, and subsequently, they founded the company Boothroyd Dewhurst Inc. (Warwick, RI, USA) in 1983 [73,74]. Since then, a series of various types of companies, including some of the largest worldwide manufacturers, have adopted DfMA methods by using these computerized packages. The approach ‘can be applied to any electro-mechanical product that requires manufacture and assembly of metallic or plastic components’ [70]. Ignoring any cultural/organizational challenges, DfMA is believed to apply equally to any industry, and commercial construction is no exception.

4.8. A Roadmap for Australian Digital Construction

DfMA must fit within a wider industry digital construction structure. In Australia’s case, it requires a paradigm shift in the way that construction is undertaken and the necessary industries that are needed to support it. There is an implied shift from onsite to offsite activity that leads to a more efficient strategy for improving the speed of project delivery, quality standards, worker safety, and waste minimization onsite. Addressing the barriers found from the present study may be better supported by the clever integration of building information modelling tools with lean construction processes as part of a proposed strategy leading to smarter (more productive) and better (more sustainable) outcomes based on growth in digital construction practices.

In Australia and the United States, there has been a growing interest in the connection between BIM, integrated project delivery (IPD), and lean construction (LEAN) and a realization that all three need to work together on large and complex projects [75,76]. This is also evident in postgraduate education initiatives applied to the construction industry, such as the Master of Science in Integrated Project Delivery at The University of Hong Kong [77] and the Master of Building Information Modelling and Integrated Project Delivery at Bond University [78]. There are new initiatives taking place in Australia concerning digital twin technologies [79] and optimizing analytics aimed at measuring project success [80].

The construction industry comprises new work, demolition, renovation and maintenance of buildings, and infrastructure. Major sectors comprise residential, commercial, industrial, and civil. Each embraces services ranging from planning and surveying to finishing work such as painting and decorating [17].

The Australian government co-funds the Industry 4.0 CRC. It was established in 2020 and aims to help develop an advanced manufacturing sector, delivering better buildings at lower cost [81]. Amongst its goals is improved and safer construction assembly through ‘DfMA processes and smart engagement with changing construction sites’. Industry-led groups such as this are likely to facilitate the transition to OSM integration.

Smarter outcomes imply speed, quality, and safety improvements achieved through OSM, while better outcomes imply less defects and errors achieved through simplified onsite assembly. Through effective design, DfMA can optimize manufacture and assembly to ensure waste minimization and sustainability. Figure 2 proposes a conceptual framework for more productive and sustainable outcomes.

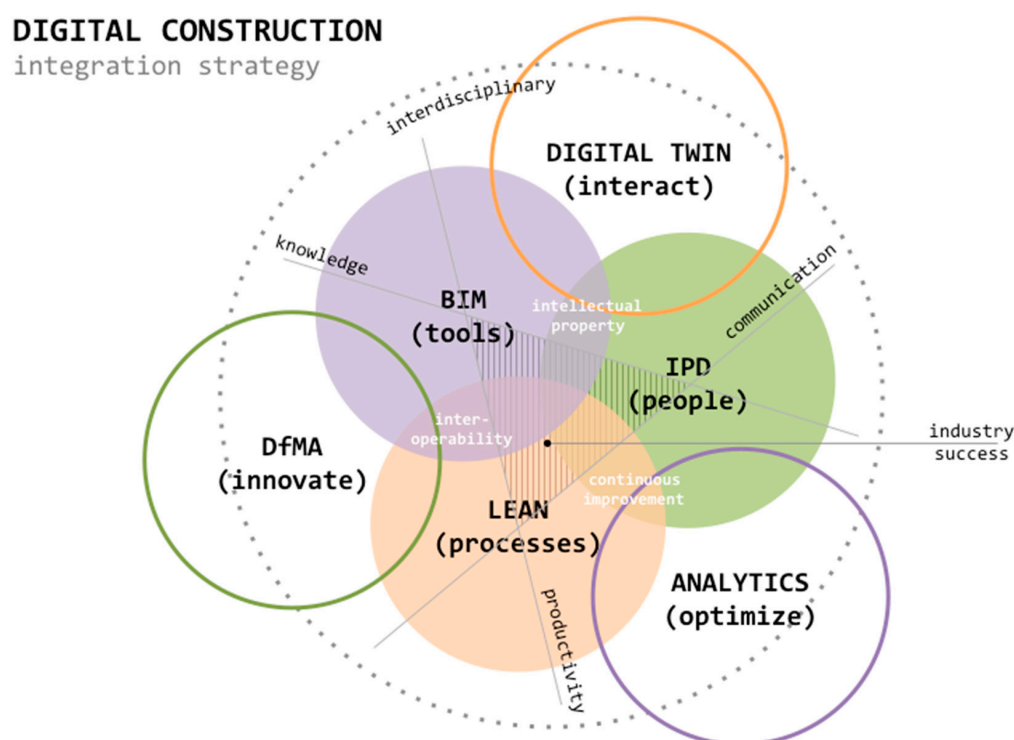


Figure 2. Proposed conceptual framework for commercial construction in Australia.

The central nexus comprising BIM, IPD, and LEAN supports improved knowledge, communication, and productivity (respectively) for Australian construction projects and supports the alignment of tools with people and processes as the basis for a new integration strategy. The interfaces of intellectual property, continuous improvement, and interoperability have advanced as potential drivers of change.

BIM includes geometry and visualization (3D), schedule optimization (4D), cost analysis (5D), environment sustainability (6D), facilities management (7D), occupational health and safety (8D), repurposing (9D), etc. IPD includes contractual relationships that underpin a no-blame collaborative team culture for the procurement of complex projects. LEAN is a mindset based on the principles of maximizing client value and minimizing unnecessary effort, creating an efficient workflow production system free from redundancy.

Our appetite for onsite activity limits ambitions to work smarter and better to attain faster completion times, fewer mistakes (defects), and less accidents and injuries. DfMA demands widespread interoperability. Offsite manufacture under controlled conditions, precision modularization, and fast-tracked are more sustainable and unlock future deconstruction and recycling options. Digital twin technologies extend static BIM models to real-time evidence-based monitoring that support post-handover interaction through the clever use of embedded sensors such as IoT 4.0 connectivity and open data exchange. Finally, actual performance must be evaluated analytically to ensure that continuous improvement is based on mandatory learning cycles from past successes and failures.

The deployment of DfMA strengthens the design phase of project delivery and leads to likely productivity gains in terms of speed, quality, human safety, and environmental performance during construction. Factory-based manufacture is largely unaffected by outside weather conditions, worker heat stress, and machine hazards that all add risk to onsite workplaces. DfMA may not lead to immediate savings, but efficiencies are anticipated over the long term as new manufacturing capacity comes online and as economies of scale place negative pressure on production inputs. Jobs will be transferred progressively from onsite to offsite locations, building specialist skills and better promoting a culture of research and development excellence. Digital twin technologies collect robust data and create stronger knowledge exchange between designers and end-users. They communicate the

analytics for effective monitoring and performance optimization to ensure the realization of expected benefits.

The integration strategy necessary to underpin industry success involves all parts working together in unison and forms a roadmap towards a more mature digital construction industry. It amplifies how tools can optimize, people can innovate, and processes can interact and establishes the architecture for future built environment technologies and innovations to plug-in.

4.9. Limitations

There are limitations in this study that should be noted. First, the study recognizes that only using qualitative methods limits the investigation of DfMA adoption in the Australian construction industry. Any hypothesis will not be proved or disproved through interview research with a small group of select experts [82]. Further quantitative or multi-method studies across a wider selection of countries would be of the utmost importance to conduct a deeper analysis and to reduce the barriers caused by single-source data collection and to improve the reliability and validity of results [56]. Therefore, the present study should be considered an exploratory investigation.

Moreover, the subjectivity of the authors and experts could be a drawback of the present study. On one hand, some aspects, including the reasons that the experts provided, were based on their knowledge, experience, and subjective reasoning. On the other hand, data analysis could be impacted by the interviewer's judgments and personal biases.

Finally, the examination of additional case studies would form part of a wider and more extensive study into the benefits of DfMA applied to construction [83–85]. There are commercial case studies being completed more frequently now than in the past. This enquiry is critical but is beyond the scope of this paper. Therefore, the present study acts as a qualitative prelude to quantitative evaluations of DfMA performance in practice.

5. Conclusions

DfMA has gained momentum in the global construction industry in recent years. Some countries and regions have advocated DfMA and have adopted it as a key strategy to achieve faster, cheaper, and better construction outcomes. However, the benefits of employing DfMA in the Australian construction industry are not yet clear.

The findings show that DfMA has potential in Australia. The case studies demonstrate local capability for DfMA in the context of stackable structural modules, but as they are all from a single contractor, they provide evidence that the widespread adoption of DfMA in large-scale buildings is still embryonic. This research concentrated on the reasons why the Australian construction industry has been slow to embrace the widespread use of DfMA. Community mindset, government regulations and incentives, planning and building codes, unionization and business politics, finance, and supply chain management were identified as key barriers to adoption.

The barriers that were identified in this study are not exhaustive. Further studies are recommended to collect data from various roles or stakeholders such as designers, architects, structural engineers, sales, and customers. Quantitative analysis of completed case studies is necessary to demonstrate success. The proposed conceptual framework for digital construction underpins future developments for DfMA, especially with respect to BIM, IPD, and LEAN practices becoming routine.

Addressing these barriers may be better supported by the clever integration of building information modelling tools with lean construction processes as part of a proposed strategy leading to smarter (more productive) and better (more sustainable) outcomes based on growth in digital construction practices. Financial, social, and environmental (or triple bottom line: TBL) aspects were not mentioned in this paper, but it might be implied that smarter (including faster and cheaper) and better are just an alternate lens to TBL for thinking about wider benefits of change. For example, completing projects faster is largely dependent on shifting work from onsite to offsite (social ramifications), and the efficiencies

that arise from offsite manufacture if scaled to an industry-wide level will likely lead to lower costs (financial ramifications). Controlled offsite manufacture can minimize waste, while assembly onsite can reduce defects and rework and support future deconstruction and recycling (environmental ramifications). This paper's title refers to a more productive and sustainable construction industry and thus implies the need to integrate financial, social, and environmental outcomes, as they are all relevant in one way or another.

The implications of this study for the Australian construction industry center on the importance of an integrated strategy to support DfMA adoption. A paradigm shift is needed from building activities predominantly with an onsite workforce to the greater use of offsite manufacture and simplified onsite assembly. This will take time and implies political negotiations with unions and incentives to develop the manufacturing capacity of the Australian economy. The latter has currency, given the impact of COVID-19 on supply chains and past reliance on imported materials, particularly from China, in the context of shifting geopolitical tensions over the appropriate balance between globalization and protectionism. If, indeed, Australian manufacturing is to be strengthened, then the construction industry makes a strong case for investment (led by government incentives and updated building regulations), given that it can unlock substantial productivity and sustainability benefits. A 'made in Australia' mindset will lead to more local job opportunities and research into innovative products that may counterbalance present concerns over modular and prefabricated design. DfMA benefits can make the Australian economy more resilient and can help transform our present malaise into a hopefully brighter post-pandemic world.

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Data Availability Statement: Transcripts of interviews were completed. However, due to confidentiality agreements, these have not been made available online.

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Abbreviations

AUD	Australian Dollars
BCA	Building and Construction Authority
BIM	Building Information Modelling
BUHREC	Bond University Human Research Ethics Committee
CBD	Central Business District
COVID-19	A disease caused by the SARS-CoV-2 virus
CRC	Collaborative Research Center
CTBUH	Council of Tall Buildings and Urban Habitat
DfA	Design for Assembly
DfM	Design for Manufacture
DfMA	Design for Manufacture and Assembly
DfX	Design for Excellence
GDP	Gross Domestic Product
HBS	Hickory Building System
IoT	Internet of Things

IPD	Integrated Project Delivery
LEAN	Lean Construction
MiC	Modular Integrated Construction
MMC	Modern Methods of Construction
OSM	Offsite Manufacture
PPVC	Prefabricated Prefinished Volumetric Construction
QR	QR (Quick Response) Code
RFID	Radio Frequency Identification
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
UK	United Kingdom

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